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Socioeconomic Impacts and Land Use Change of Integrating Biofuel Production with Livestock Farming in Brazil: A Computable General Equilibrium (CGE) Approach

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ABSTRACT

Sugarcane bioenergy is a reality in Brazil, comprising the production of ethanol and bioelectricity. Sugarcane bioenergy can reduce greenhouse gas (GHG) emissions as compared to fossil fuels. However, there are concerns about the possible implications caused by the expansion of sugarcane production, the displacement of mainly pastureland, but also other croplands, and the potential for indirect land use changes. A promising strategy to enlarge sugarcane bioenergy in Brazil without compromising the cattle industry is to integrate both activities, converting extensive livestock production systems into more intensive ones. The objective of this study is to model and evaluate the socioeconomic impacts and land use change considering the expansion of ethanol production in two scenarios. The first scenario, referred to Business as Usual (BAU), comprises of sugarcane bioenergy and extensive livestock production, without any integration between the two. The second scenario, Integrated Sugarcane-Bioenergy and Livestock (ISBL) in Brazilian agriculture, considers the integration between these activities. To achieve this goal, a computable general equilibrium (CGE) model for the Brazilian economy was implemented. The Brazilian input-output matrix (main data for the model) was estimated for 2021. The closure and the shocks were set to 2031, with an estimated increase of 75% in ethanol production. Additionally, a technological efficiency gain of 5% was considered for the livestock sector within the ISBL system. Our modeling results show that the ISBL scenario is economically more efficient, as a higher gross domestic product and output level were obtained. The aggregate employment level of the economy also increased. Even considering that the integration of sugarcane bioenergy and livestock production took place only in these activities, positive socioeconomic impacts were noticed across other sectors of the economy.

Keywords: Ethanol, Biomass, Modelling and Simulations, Renewable and Sustainable Energy, Energy Policy

1 INTRODUCTION

The increasing global pressure to reduce greenhouse gas (GHG) emissions and increase sectors' efficiency have driven significant transformations in energy consumption patterns and production models. In this context, biofuels emerge as a strategic solution, particularly ethanol, whose use can reduce up to 90% of CO_2 equivalent emissions compared to gasoline [1]. However, the expansion of biofuel production in Brazil faces complex challenges, ranging from direct environmental impacts, such as those related to the intensive use of agrochemicals and biomass burning, to indirect ("leakage") impacts, such as the displacement of traditional agricultural activities with potential pressures on native ecosystems and to food security [2].

The fulfillment of international emission control agreements is directly linked to reducing deforestation in Brazil, as the agricultural and land-use sectors are the main contributors to GHG emissions in the country, accounting for ca. 75% of Brazil's emissions in 2021 [3]. Indirect land use changes (ILUC), for example driven by ethanol expansion, are a point of consideration, as they might pose pressures to expand deforestation in the Cerrado and Amazon biomes, compromising the achieved levels of GHG emission reductions in addition to the impacts to biodiversity and the environment. Also, displaced livestock and agricultural activities may face output constraints, jeopardizing economic output, employment levels, and food security. In this context, public and private initiatives targeting sustainable intensification approaches have gained relevance and are creating opportunities to transform the externalities of agricultural production into economic, social, and environmental advantages.

Thus, expanding biofuel production, combining the environmental benefits of being a cleaner fuel with the possibility of reducing environmental impacts, becomes a key strategy for Brazil. The integration of sugarcane production with livestock and bioenergy can enhance the efficient use of existing pasture areas and potentially recover degraded pastures, without compromising the level of production.

The integration of biofuel production with livestock farming offers several advantages to the Brazilian economy. Among them, it allows for the use of existing infrastructure and the production of co-products from biorefinery, contributing to the reduction of feeding costs for confined livestock and, at the same time, reducing the need for new areas for raising animals. This allows producers to diversify their activities and maximize the use of their land, creating a more sustainable and efficient economic cycle. Also, backward and forward spillover effects are expected in this process, benefiting other sectors in the economy.

Therefore, the main research question to be addressed in this work is expressed as follows: what are the socioeconomic and land use impacts of the expansion of ethanol production in Brazil, and how does this transformation potentially influence the production levels of the main agricultural sectors, the gross domestic product (GDP), and employment in the country?

2 METHODS

The method adopted in this study is based on the development and application of a Computable General Equilibrium (CGE) model for the Brazilian economy, implemented using the GEMPACK v.12 interface with the MINIMAL version [4]. The following key assumptions establish the fundamental framework for the analysis, providing a clear foundation for projecting the effects of ethanol production expansion:

- *Period under analysis:* The study considered a 10-year period, given the fact that the effects of the integration between sugarcane production for bioenergy and livestock farming, as well as changes in land use and agricultural practices, involve costs and require more complex planning, which demands a longer time horizon. Thus, it was focused on the projections and impacts of ethanol production expansion from 2021 (admitted as the first recovered economic year after the Covid-19 crisis in 2020) until 2031. Ethanol expansion followed RenovaBio's target as a policy scenario [5].
- *Input-Output Matrix:* The study utilized the Input-Output Matrix (IOM) for 141 sectors of the Brazilian economy, providing a detailed analysis of the economic impacts of ethanol production expansion across various productive sectors and supply chains. The IOM was estimated for the year 2021, ensuring an up-to-date representation of sectoral interactions.
- *Ethanol Production:* The study considered a 75% increase in hydrated ethanol production, according to the projections established by RenovaBio [5]. This increase was modeled within the IOM, evaluating the effects on other sectors of the economy.
- *Gasohol Usage:* For analytical purposes, it was assumed that there would no substantial changes in the use of gasohol, allowing the isolation of the impacts of expanding hydrated ethanol production, without external interference related to changes in gasohol usage policies.
- *Total Land in Brazil:* Given the government's commitment to achieving zero deforestation by 2030, it is assumed, as a limiting condition, that no additional land beyond the total available in 2021 will be accessible to any economic sector. Consequently, the expansion of ethanol production will not lead to new deforestation or conversion of native vegetation areas. On the contrary, its expansion should be based only on displacing other agricultural activities, as degraded pastureland [6].

2.1 Description of scenarios

To analyze the impacts of expanding ethanol production in Brazil, two distinct scenarios were defined: the

BAU (Business as Usual) Scenario and the ISBL (Integrated Sugarcane-Bioenergy and Livestock) Scenario. Each of these scenarios reflects different development trajectories, considering the growth assumptions of the ethanol sector, land use, and interactions with other economic activities, such as livestock farming.

2.1.1 The BAU Scenario

This scenario assumes continuity of the current model, with bioenergy production from sugarcane and extensive livestock farming without integration between the activities, representing the most likely production pattern in Brazil.

2.1.2 The ISBL Scenario

This scenario proposes the integration of sugarcane production for bioenergy with livestock farming, aiming at more efficient land use and intensification of production. It is assumed that all the released pasturelands will be used for sugarcane production.

2.2 Technological efficiency change

To estimate the change in technological efficiency between a representative cattle management system in Brazil and an integrated system, we analyzed the variation in total production cost per carcass between the two models. It was assumed that the unit total cost serves as a good technological indicator, as it reflects the use of primary factors (land, labor, and capital), input consumption, and productivity.

Brazilian cattle farming in 2021 is characterized by the following data: pastureland covers 161.7 million hectares [7]; the total cattle herd consists of 224.6 million heads, with 27.7 million slaughtered annually [8]; among these, 6.5 million are finished in feedlots [9]. Annual beef production reaches 7.456 million tons of carcass equivalent. Based on these figures, the estimated average stocking rate in Brazil is 1.3 heads per hectare. Additionally, it was assumed that conventional management in Brazil involves pasture renewal every five years.

The ISBL system, on the other hand, consists of a first-generation ethanol plant with vinasse biodigestion for electricity generation [10-12]. The selected plant capacity was 4 million tons of sugarcane per year (4MTC/year), which is considered close to the optimal capacity for the biorefinery [13]. This corresponds to a sugarcane plantation area of 64.5 thousand hectares and an annual ethanol production of 345 million liters. Furthermore, it was assumed that soybeans are grown during sugarcane reform and processed at the plant, with by-products such as soybean meal used in animal feed. It was also assumed that all cattle are finished in feedlots, leading to an annual beef production of 60 thousand tons of carcass equivalent [13].

Based on these data and assumptions, production costs were estimated using a techno-economic model developed by Embrapa Digital Agriculture. The estimated cost for the conventional Brazilian system, considering an exchange rate of 1 USD = 6 BRL and a historical average of key input prices in the model, was 3.2 USD/kg of carcass equivalent. In the integrated system, this cost was lower, reaching 2.8 USD/kg of carcass equivalent. When accounting for the total carcass production in each system, this cost variation translates into a -5% difference, indicating an improvement in technological efficiency in the integrated system compared to the conventional one.

2.3 Closure of the General Equilibrium Model

For both scenarios, exogenous variables were defined for the general equilibrium model closure, as presented by Horridge (2001) [4]:

- Exchange rate (local currency/foreign currency);
- Wage rate, adjusted by the Consumer Price Index (CPI);
- Gross rate of return;
- Total land area available;
- Ordinary change in the import tax rate;
- Ordinary change in the domestic tax rate, except for the hydrated ethanol sector;
- Use of composite goods by the investment sector;
- Use of composite goods by the government;
- World prices, measured in foreign currency;
- Quantity shift in foreign demand;
- All primary factors augmenting technical change;
- Industrial production of hydrated ethanol and gasohol.

As established, a 75% shock in hydrated ethanol production was applied to both scenarios. In addition to this initial shock, a sensitivity analysis considering variations relative to the original shock of ±50% (e.g. 37.5% and 112.5% range) was modeled. Based on these results, the mean and standard deviation were calculated. Using Chebyshev's theorem, a confidence interval of 88.9% was determined, considering three standard deviations [14].

In the ISBL scenario, in addition to the hydrated ethanol shock, an additional -5% shock was applied to all primary factors augmenting technical change in the livestock sector, as previously estimated. Furthermore, in ISBL, land allocated to agricultural crop sectors was defined as exogenous, replacing the ordinary change in the domestic tax rate for these sectors, which became endogenous.

3 RESULTS

In the analysis of the results, the percentage variations in primary factors, total output, household consumption, exports, and domestic taxes and macoeconomics were assessed for key sectors of the Brazilian economy directly related to the study. The analysis was conducted for the BAU and ISBL scenarios, with the difference between them (ISBL – BAU) referred to as Delta.

3.1 Primary factors (land, capital, and labor)

The projected increase in ethanol production directly impacts Brazilian agriculture. To assess the effects of this growth on primary factors in the sector, we analyzed changes in sugarcane, corn, soybean, and livestock production, which account for the largest land area usage in the country (Figure 1).

In the BAU scenario, the expansion of sugarcane cultivation required a reduction in land used by other agricultural sectors, even though in different proportions (Figure 1A). This shift highlights the ongoing trade-off between biofuel production and food supply. Although the percentage variations appear small, particularly for corn and soybeans, their absolute impacts are significant.

In the ISBL scenario, there was a more pronounced reduction in land allocated to livestock, a direct consequence of increased efficiency through the adoption of cattle confinement in integrated systems. The freed-up land was almost entirely redirected to sugarcane production without affecting the areas allocated to other crops, which remained constant in the model closure. Additionally, the ISBL system required less land for sugarcane cultivation compared to BAU, likely due to improved efficiency in other primary factors within the sector (Figures 1B and 1C).

The increase in ethanol production also led to a higher demand for labor and capital in the sugarcane sector in both scenarios, with a slightly greater increase in ISBL compared to BAU (Figures 1B and 1C). A similar trend was observed for the corn and soybean sectors, although the rise in primary factors was more pronounced in the ISBL scenario. For the livestock sector, variations in these factors were minimal in both scenarios. However, in ISBL, the variation was even smaller, with a negative impact on capital stock, reflecting improvements in the sector's technological efficiency.

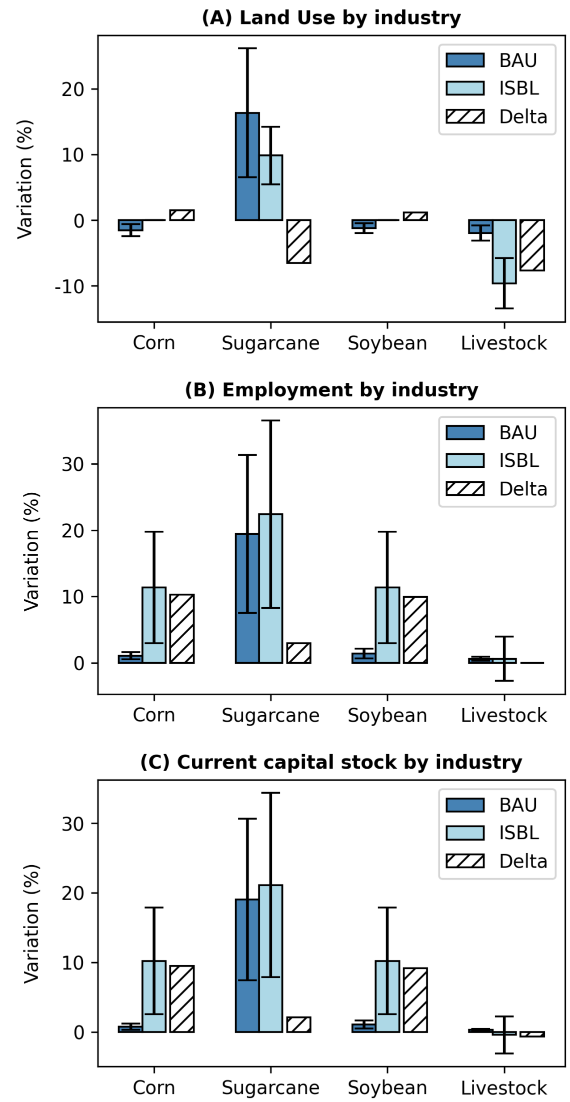

Figure 1. Variation in the primary factors of some sectors of the economy. For BAU and ISLB, the 89% confidence interval is indicated.

3.2 Total output

Another important aspect of the general equilibrium analysis is the total output across sectors (Figure 2). In addition to sugarcane, corn, soybean, and livestock sectors, the analysis also included beef production and certain fuels, such as gasoline A and anhydrous ethanol. The production of these sectors, along with many others, increased in the scenario projecting a 75% expansion of hydrated ethanol. While the difference between ISBL and BAU scenarios is small for sugarcane production, it becomes more pronounced in other sectors, particularly for corn, soybeans, and beef.

Furthermore, an increase in the production of other fuels is observed, likely as a consequence of the higher productive use in other economic sectors that require these fuels in their pure form.

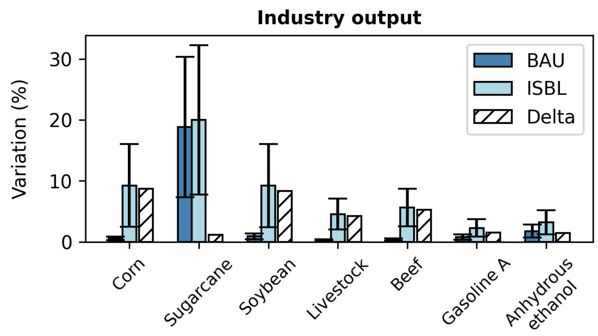

Figure 2. Variation in total production in some sectors of the economy.

3.3 Household consumption and exports

Household consumption in the beef sector showed a significant increase in the ISBL scenario, while it remained practically unchanged in BAU (Figure 3A). On the other hand, the consumption of gasoline A and anhydrous ethanol decreased in both scenarios, with a more pronounced reduction in ISBL. This decline is likely explained by the increase in exports of these fuels (Figure 3B).

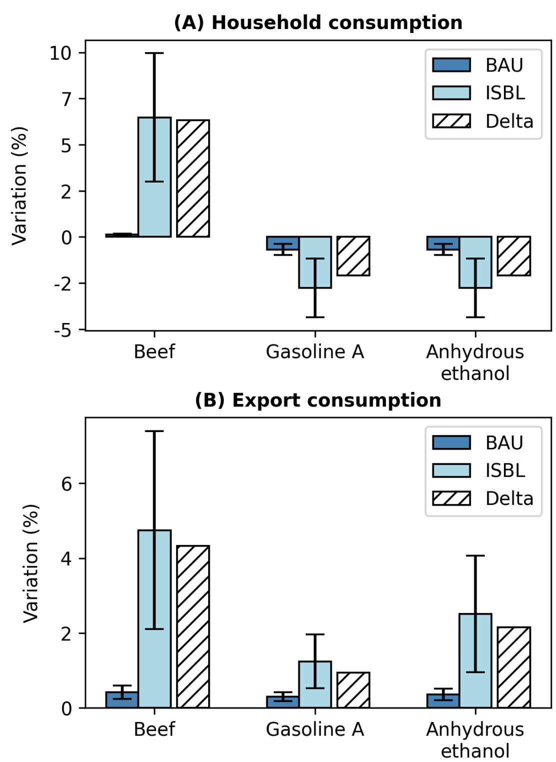

Figure 3. Variation in household (A) and export consumption (B) in some sectors of the economy.

3.4 Domestic rate taxes

To facilitate the increase in hydrated ethanol production, domestic tax rates on this product were treated as endogenous variables in the ISBL scenario. Consequently, a reduction in the ordinary tax rate of -0.47 would be required for hydrated ethanol in both the BAU and ISBL scenarios. In the ISBL scenario, to validate the premise that sugarcane expansion would occur exclusively over pastureland, it would also be necessary to reduce taxes on agricultural products (Table 1).

Table 1. Variation of ordinary change in the domestic tax rate in some sectors of the economy.

Industry sector	Mean	Confidence interval
Hydrated ethanol	-0.47	[-0.62, -0.32]
Corn	-0.16	[-0.28, -0.04]
Soybean	-0.17	[-0.29, -0.05]

3.5 Macroeconomic results

Figure 4 presents the macroeconomic results of the BAU and ISBL systems after the shocks were applied, considering the proposed closure. In both scenarios, there was an increase in aggregate employment, real GDP, real household consumption, export volume index, and import volume index (Figure 4). However, when comparing the scenarios, ISBL exhibited a more significant increase than BAU.

These results suggest that a policy of expanding ethanol production over time could be beneficial to the Brazilian economy under the tested conditions and assumed premises. Additionally, it is noteworthy that land prices increased more in the ISBL scenario (18%) compared to BAU (4%).

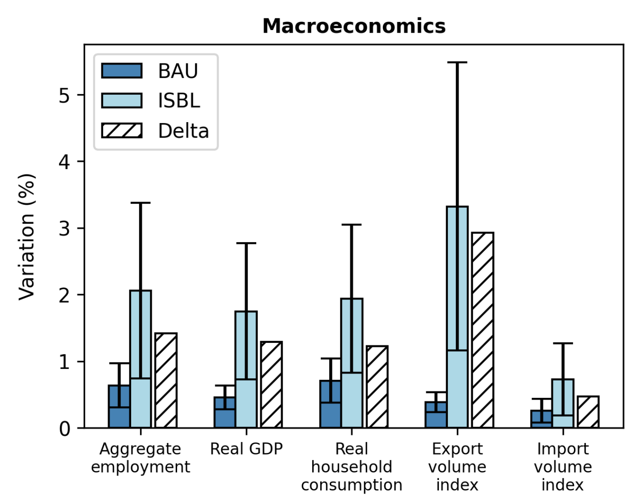

Figure 4. Variation in macroeconomic parameters.

4 CONCLUSIONS

In comparison to the business-as-usual (BAU) scenario, the ISBL scenario, under the evaluated conditions and assumptions, demonstrates higher economic efficiency and overall positive effects to other sectors.The integrated scenario makes more rational use of production factors, leading to an increase in productivity driven by technical efficiency gains. Additionally, the ISBL scenario stands out for presenting more substantial real economic growth, reflected in the increase in GDP. This scenario illustrates the potential of an initiative that can contribute to mitigating the impacts on native vegetation areas, showcasing significant potential for the recovery of degraded pastures in Brazil.

Future research is expected to disaggregate the cattle farming sectors in order to distinguish between confinement and pasture systems relative to the broader livestock sector. Furthermore, incorporating greenhouse gas emission levels from each of the economic sectors included in the model will be crucial for constructing a more complete and detailed emissions balance. This approach will allow for a more precise and comprehensive assessment of the environmental impacts associated with each production system, contributing to the understanding of their ecological and economic implications.

Finally, this study demonstrated that the expansion of ethanol production in Brazil, while representing a significant opportunity to strengthen the energy and agricultural sectors, also presents complex challenges to socioeconomic and environmental aspects. The analysis of indirect land use change (ILUC) impacts reveals that the growing demand for ethanol may lead to the intensification of agricultural production, altering the balance between different sectors of the economy and affecting land use in ways that generate both benefits and environmental costs. Additionally, the positive effects on GDP and employment emphasize the opportunities of pursuing and promoting sustainability approaches, balancing bioenergy production with environmental preservation and social well-being. In summary, for Brazil to solidify its position as a leader in ethanol production, it will be essential to adopt strategies that integrate productive efficiency, environmental protection, and social inclusion to ensure a trajectory of sustainable development in the long term.

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